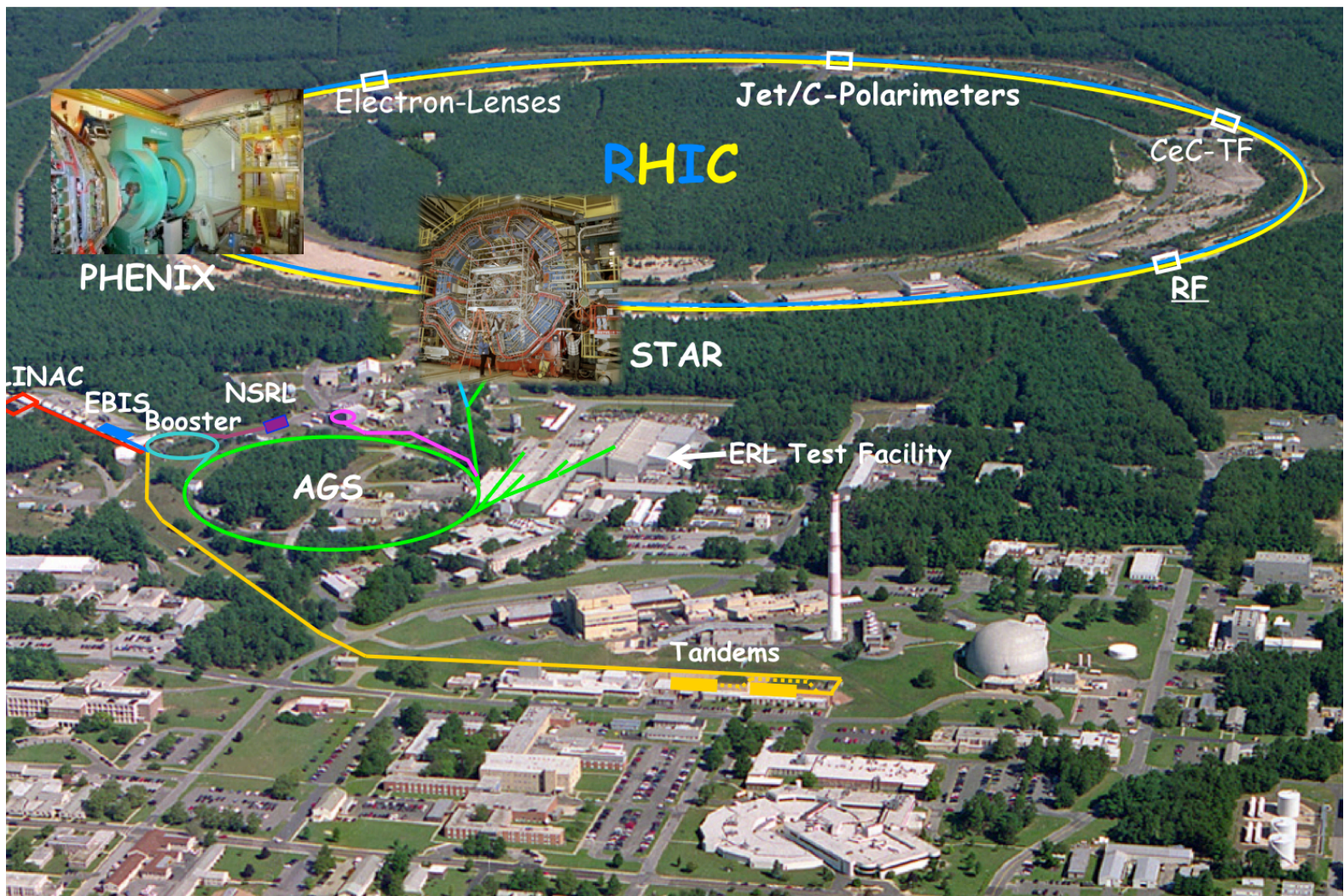


The RHIC SPIN Program

Achievements and Future Opportunities



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1 Executive Summary

Spin is one of the most fundamental and subtle concepts in physics, deeply rooted in the symmetries and structure of space-time. Spin determines whether a particle follows Fermi or Bose statistics, which has profound implications for the structure of matter and the stability of many-body systems and lays the foundations for the fields of chemistry and biology. Despite their quantum-mechanical and relativistic origins, spin effects are evident even at large scales and play a critical role in everyday applications such as nuclear magnetic resonance imaging or spintronics-based memory chips. Except for the recently discovered Higgs boson, all elementary particles we know today carry spin, among them the particles that are subject to the strong interactions: The spin-1/2 quarks and the spin-1 gluons. Spin, therefore, plays a central role also in our theory of the strong interactions, Quantum Chromodynamics (QCD), and to study spin phenomena in QCD will help to further our understanding of QCD itself. The primary goal of the spin physics program at RHIC is to use spin as a unique probe to unravel the internal structure and the QCD dynamics of nucleons with unprecedented precision.

Protons and neutrons, which make up all nuclei and hence most of the visible mass in the universe, themselves carry spin-1/2. As has been known for over eight decades now, they also possess internal structure. This insight came directly due to spin, through the measurement of a very unexpected “anomalous” magnetic moment of the proton. In fact, there is an important lesson to be learned from this discovery: Measuring the magnetic moment of the proton was not viewed as an important step at the time, because the answer was already assumed to be “known” to fairly high precision. However, this turned out to be false – and as a result we learned that the proton has substructure. This was just the first of numerous surprises related to spin in strong interaction physics, arguably culminating in the proton “spin crisis” uncovered by the EMC experiment in the late 1980s. The EMC discovery that quark and antiquark spins provide only little of the proton spin, once again, proved previous expectations to be incorrect and showed that the proton substructure was much richer than we had imagined.

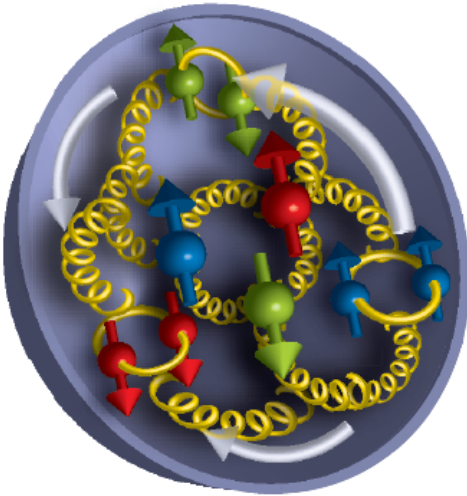


Figure 1-1: Schematic view of the proton built from quarks, quark-antiquark pairs, and gluons.

Our modern view of the proton is that of a complex system of quarks and transient quark-antiquark pairs, bound together by gluons (see Figure 1-1). The study of the inner structure of such systems that are composed of quarks and gluons is at the heart of investigating QCD in the regime where quarks and gluons interact so strongly that they are confined within hadrons. Spin plays a dual role in this context, foremost to study proton structure in its own right and thus as a tool for uncovering properties of the strong interactions. In a broad sense, RHIC investigates how spin phenomena in QCD arise at the quark and gluon level. A particularly important question, and a key focus ever

since the EMC measurements, is how quarks and gluons conspire to provide the proton's spin-1/2 through their spin and orbital angular momentum contributions.

RHIC addresses these topics in various complementary ways, making use of the tremendous versatility of the machine, which makes both longitudinal and transverse polarization of the protons relative to their momenta readily available. The focus at RHIC spin is on the following topics:

How do gluons contribute to the proton spin? Polarization of gluons in the proton has long been expected to be a source for major contributions to the proton spin. Indeed, latest data from the 2009 RHIC run with longitudinal polarization have, for the first time, provided evidence that gluons do show a preferential alignment of their spins with the proton's spin. This is a milestone for the field, offering new clues on the proton spin decomposition and on the nature of the strong force fields inside a proton. The current generation of RHIC measurements is providing information about the polarization of gluons that carry around 1% or more of the proton's momentum. Detector upgrades during the next few years will allow extending this sensitivity to gluons with even smaller momenta.

What is the “landscape” of the polarized sea in the nucleon? In order to understand the dynamics of the quark-antiquark fluctuations in the proton, one needs to learn about the up, down, and strange quark and antiquark densities, individually. This is expected to provide insight into the question of why it is that the total quark plus antiquark contribution to the proton spin was found to be so small. It is also important for models of nucleon structure, which generally make clear qualitative predictions about, for example, the flavor asymmetry in the light quarks in the proton sea. Such predictions are often related to fundamental concepts such as the Pauli principle. At RHIC one uses a powerful technique based on the violation of parity in weak interactions. The W^\pm bosons naturally select left quark handedness and right antiquark handedness and hence are ideal probes of nucleon helicity structure. Data from RHIC have now reached the precision needed for obtaining meaningful constraints on the distributions, and a significant further increase in precision is anticipated for the coming years. Comparison with data from semi-inclusive lepton scattering offers tests of basic concepts of high-energy perturbative QCD, such as the universality of parton densities.

Transverse-spin phenomena in QCD. The past decade has seen tremendous activity and progress, both theoretically and experimentally in this area. Among the quantities of particular interest are parton distribution functions that may be accessed in spin asymmetries for hard-scattering reactions involving transversely polarized protons. These distributions, known as “Sivers functions”, express correlations between a parton's transverse momentum inside the proton, and the proton spin vector. As such they contain information on orbital motion of partons in the proton. It was found that the Sivers functions are not universal in hard-scattering reactions. This by itself is nothing spectacular; however, closer theoretical studies have shown that the non-universality has a clear physical origin that may broadly be described as a rescattering of the struck parton in the color field of the remnant of the polarized proton. Depending on the process, the associated color Lorentz forces will act in different ways on the parton (see Figure 1-2). In deep-inelastic scattering (DIS), the final-state interaction between the struck parton and the nucleon remnant is attractive. In contrast, for the Drell-Yan process it becomes an initial-state interaction and is repulsive. As a result, the Sivers functions contribute with opposite signs to the single-spin asymmetries for these two processes. This is a fundamental prediction about the nature of QCD color interactions, directly rooted in the quantum nature of the interactions. The Sivers effect exhibits direct physical implications of the gauge potential in a similar way as the Aharonov-Bohm effect does in Electrodynamics. It tests all the concepts for analyzing hard-scattering reactions that we know of. Studies have begun at RHIC

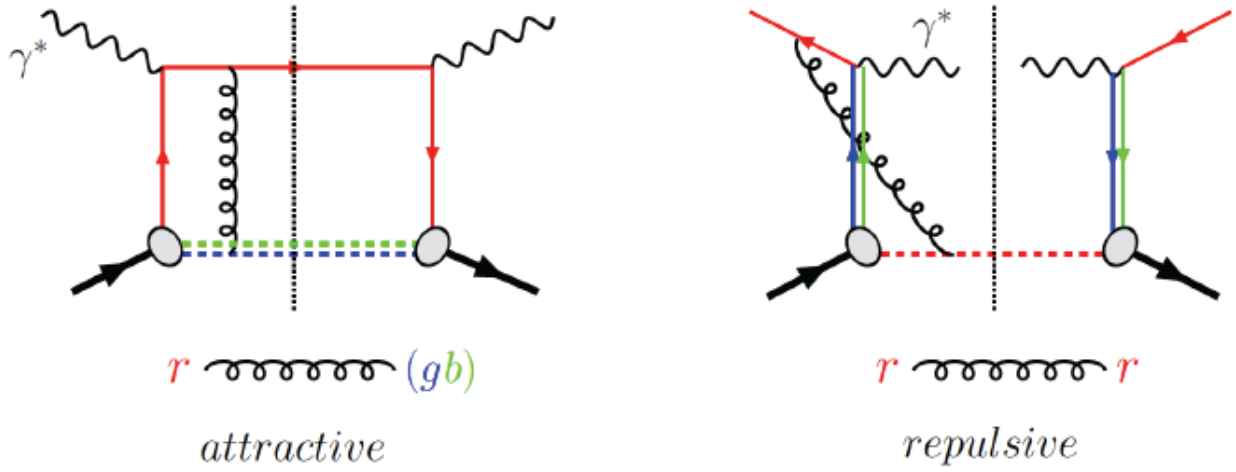


Figure 1-2: Final-state and initial-state color interactions in deep-inelastic lepton nucleon scattering (left hand side) and the Drell Yan process (right hand side).

aiming at verifying this prediction, which would be a milestone for the field of hadronic physics.

Time and again, spin has been a key element in the exploration of fundamental physics. Spin-dependent observables have often revealed deficits in the assumed theoretical framework and have led to novel developments and concepts. The pseudo-scalar nature of spin is exploited in many parity-violating experiments searching for physics beyond the Standard Model or studying the nature of nucleon-nucleon forces. The RHIC spin program plays a special role in this grand scheme: It uses spin to study how a complex many-body system such as the proton arises from the dynamics of QCD. Many exciting results from RHIC spin have emerged to date, most of them from RHIC running after the 2007 Long Range Plan. In this document we present some of the highlights of the program so far and lay out the roadmap for further significant advancements of the field to be expected from future RHIC operations.

2 Introduction and Achievements since the last Long Range Plan

2.1 The Helicity Structure of the Proton

2.2 Confined Motion of Partons in Nucleons: TMDs

3 Unique opportunities with polarized protons at RHIC in the coming years

3.1 The Helicity Structure of the Proton

3.2 Confined Motion of Partons in Nucleons: TMDs

3.3 Detector upgrades

4 Summary

5 Appendix

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